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by Milton D. McLaughlin

Langley Research Center
Langley Station, Hampton, Va.

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SUMMARY

A preliminary investigation has been made of airspeed increases from upsets in pitch, push-overs, longitudinal trim runaways, and abandons of controls and simulated operations in the air traffic control (ATC) system for a generalized double-delta supersonic transport (SST) configuration for the purpose of assessing the overspeeding in relation to the tentative speed margin. A piloted fixed-base aircraft simulator was used in the investigation. Tests were made for climb, level flight, and descent conditions along the maximum operating limit speed profile. Results show that at supersonic speeds the 7.5° upset maneuver, currently proposed as a standard for establishing a speed margin, provided a margin greater than the speed excursions resulting from other maneuvers. The 7.5° upset maneuver, however, may be unsuitable for establishing overspeed criteria for the SST at supersonic speeds because of the increase in entry times over subsonic values. A constant acceleration push-over type of maneuver appeared to be more rational at supersonic speeds. In operations in the simulated ATC system, the pilots recommended that, in order to avoid frequent overspeeds, the climb profile should be a minimum of at least 10 to 20 knots below the maximum operating limit speed.

INTRODUCTION

Federal Aviation Regulations for transport airplanes (ref. 1) require a speed margin between maximum operating limit speed and the design diving speed to provide for inadvertent speed increases caused by such factors as upsets due to autopilot failure, potential energy and/or thrust mismanagement, and atmospheric changes such as horizontal wind gusts or temperature variations. The existing speed margins are based on experience gained in routine operations. There is, however, no operational experience on which to base the speed margin requirements for the supersonic transport (SST). Tentative standards which are being used in the National SST development program are the same as current standards for subsonic speeds, while arbitrary minimum margins have been established at supersonic speeds. Since any excess speed-margin requirement is detrimental to airplane performance and since insufficient margins are detrimental to safety, it is important to obtain information on which to establish rational speed margins for the SST as early as possible in the design phase.

During the course of a joint NASA-FAA simulator study of operating problems of the SST in the air traffic control (ATC) system, an opportunity arose to obtain results on overspeeding during climbouts and descents in simulated routine airline-type operations as well as results of airspeed increases in specific maneuvers. The specific maneuvers investigated were (1) upsets in pitch, (2) push-overs at normal acceleration of 0.5g, (3) runaway pitch trim control, (4) abandon of controls in a 45° bank, and (5) thrust mismanagement in level offs from climbouts (for both tunneling operations following take-off and step climbs at higher altitudes). Data and pilots' opinions relative to practical operating speeds were obtained in climbouts. A description of the SST-ATC simulator has been reported in reference 2. The fixed-base SST simulator was operated under manual control by NASA test pilots and airline pilots for these studies. The tests covered Mach number and altitude ranges from take-off to cruise conditions. The overspeeding results obtained are compared and discussed relative to the tentative standards (ref. 3) being used in the SST development program.

SYMBOLS AND ABBREVIATIONS

Δa_X	change in longitudinal acceleration, g units
a_Z	normal acceleration, g units
D	drag, pounds (newtons)
h	altitude, feet (meters)
Δh	departure from initial altitude, feet (meters)
M	Mach number
M_D	design dive Mach number as defined in reference 1
M_{MO}	maximum operating limit Mach number as defined in reference 1
T	thrust, pounds (newtons)
t	time, seconds

$t_{1/2}$	time to damp to one-half amplitude, seconds
V_D	design dive speed as defined in reference 1
V_{MO}	maximum operating limit speed as defined in reference 1
V_i	indicated airspeed, knots
ΔV_i	departure from initial indicated airspeed, knots
V_2	initial climb speed, knots
W	weight, pounds (newtons)
δ_e	longitudinal control deflection, degrees
θ	pitch angle, degrees
A/B	afterburner
ATC	air traffic control
IAS	indicated airspeed
KIAS	knots indicated airspeed
SST	supersonic transport

SST SIMULATION

The SST was simulated by use of a fixed-base aircraft flight compartment linked to an analog computer facility. The flight compartment was representative of current jet transport types (fig. 1) with stations for captain, first officer, and flight engineer. Airplane control was effected through conventional control column, rudder pedals, throttles, and trimming arrangements. The flight controls had linear force characteristics with positive centering. The flight instruments (fig. 2) were similar to those used in current jet transports and included a flight-director system. Extended ranges were provided on the airspeed, Mach number, rate-of-climb, and altitude displays to cover SST operations. The airspeed display included a maximum operating speed limit needle. An overspeed warning horn was activated to sound at 6 knots above the maximum operating speed limit. Since no acceleration cues were available to the pilot because of the lack of motion, a warning light on the instrument panel was used to indicate the exceedence of an increment of 0.3g in normal acceleration in either direction from a 1.0g value.

The analog computer was programed with six-degree-of-freedom motion equations and the physical, aerodynamic, and control characteristics of a generalized double-delta SST configuration (table I).

OVERSPEED PROBLEM FOR THE SST

The tentative standards (ref. 3) for maximum operating speeds established for the National SST development program required that a margin be provided to allow for inadvertent overspeeds resulting from either (1) a specified upset maneuver in pitch or (2) miscellaneous causes such as atmospheric variations, instrument errors, and airframe production variations, whichever is the greater, without exceeding the design dive speed. The specified upset maneuver is the same as current standards and is described in the section "Test Procedures and Tests." The minimum overspeed margin specified for miscellaneous causes is 0.05M for subsonic speeds up to $M = 0.95$, and 0.20M for $M = 1.5$ and above, with a straight line variation of the minimum overspeed margin between $M = 0.95$ and 1.5.

With the use of the 7.5° upset maneuver, a speed margin was calculated for the SST design used in this study and is presented in figure 3. Shown are the initial conditions of altitude and airspeed on the curve for maximum operating limit speed V_{MO} and the calculated design dive speeds V_D, which establish the design dive speed curve. In the calculations the aircraft was assumed to be instantaneously upset 7.5° from an initial stabilized flight-path angle at V_{MO} or M_{MO}, flown for 20 sec along a flight path 7.5° below the initial flight path, and recovered by a pull-up maneuver at a load factor of 1.5g. The calculations were made for the descent cases as these exhibited the largest overspeed margins. The initial stabilized flight-path angles and the altitudes used were -6.5° at 10 000 ft (3.0 km), -6.5° at 30 000 ft (9.1 km), -5° at 41 000 ft (12.5 km), -3° at 55 000 ft (16.8 km), and -1° at 71 000 ft (21.6 km). Simple point mass calculations were used to determine speed increases and the level-off times and simple geometric considerations, to determine altitude loss. The longitudinal forces considered were thrust, drag, and gravity component. The effects of altitude and airspeed changes on thrust and drag during the run were not considered. At altitudes up to 71 000 ft, the upset maneuver was the determining factor in establishing the margin. At altitudes above 71 000 ft, the speed margin was established by the "miscellaneous causes" requirement. The design dive speed V_D for a calculated optional method of $V_D = 1.25V_{MO}$ is shown in figure 3. It can be seen that the method would allow a smaller speed margin at altitudes from about 30 000 ft (9.1 km) to 60 000 ft (18.3 km) than the upset maneuver margin. No consideration of this method has been given in the rest of this report since the FAA has eliminated it in a revision to the Tentative Airworthiness Standards for the Supersonic Transports (ref. 4), issued subsequent to these tests.

Also shown in figure 3 are the climb and descent profiles and lines of constant Mach number for $M = 1.0$ and 2.0. The climb and descent profiles were used in the simulated airline-type operations. It can be seen that in climbout, the SST was operated at or near V_{MO} at the lower altitudes and between about 55 000 and 71 000 ft (16.8 and 21.6 km). In the altitude range between about 40 000 and 55 000 ft (12.2 and 16.8 km), operating climb speeds for the SST fall well below V_{MO} because of speed restrictions imposed by the sonic-boom overpressure limitation. Above 71 000 ft (21.6 km), the SST was climbed at M_{MO}. In descent, the SST was scheduled to be operated considerably below M_{MO} and V_{MO} at altitudes above 30 000 ft (9.1 km).

It can be seen from the relationships of the actual operating speeds to the maximum operating speeds (fig. 3) that the probability of overspeeding for the SST is greatest at low altitudes (below about 30 000 ft) and at high altitudes approaching the beginning of cruise. In the low-altitude region, the overspeeding problem for the SST is accentuated by an excess thrust-weight capability considerably greater than that of subsonic jet transports. At the high altitudes, speed control for the SST is further complicated by the increased period of the phugoid motion and the increased kinetic energy change resulting from a given change in flight-path angle. However, the time to change or correct the flight path is increased if maneuvering loads are kept at present passenger comfort levels.

TEST PROCEDURES AND TESTS

The SST simulator was operated under manual control for all tests, with guidance supplied entirely by the aircraft flight and navigation instruments. The specific maneuver tests were performed by two NASA test pilots. The measurements of inadvertent speed increases during simulated operations in the air traffic control system were obtained with piloting performed by four airline crews (eight pilots). The equipment and procedures used in the SST-ATC studies are described in reference 2.

Time histories of altitude, Mach number, indicated airspeed, vertical speed, control surface position, angular attitudes and velocities, normal acceleration, thrust, drag, and throttle positions were recorded for each test.

Upset, Push-Over, Longitudinal Trim Runaway, and Abandon Maneuvers

The upset, push-over, longitudinal trim runaway, and abandon maneuver tests were performed at several Mach numbers at the maximum operating limit speed between altitudes of 10 000 and 70 000 ft (3.0 and 21.3 km). The upset and push-over maneuvers were initiated from both climbing and level flight and additional upset maneuvers were made from descending flights. The longitudinal trim runaway and abandon maneuvers were initiated from level flight. For climbing flight, minimum afterburner thrust was used at altitudes up to 29 000 ft (8.8 km) and maximum afterburner thrust, at altitudes above this level. Trim thrust settings were used for level-flight tests, and idle thrust settings were used for descent tests. For the trim runaway tests, both trim and maximum afterburning thrust settings were used.

The upset maneuver which is used in establishing current minimum overspeed margins (ref. 1) was an instantaneous 7.5° flight-path-angle change from stabilized flight at V_{MO}, or M_{MO}, flight for 20 sec along a flight path 7.5° below the initial path, and pull-up at a load factor of 1.5g. For the 20-sec part of the upset maneuver, runs were made both with "hands on" and with "hands off." For the "hands on" runs, the pilot attempted to hold the upset flight path by holding the normal acceleration at $1.0g \cos \gamma$ where γ is defined as the flight-path angle measured from the horizon. For the "hands off" runs the pilot kept his hands off the controls until start of recovery. The initial stabilized flight-path angles and altitudes investigated were 0° and -6.5° at 30 000 ft (9.1 km), 3°, 0°, and -3° at 54 000 ft (16.5 km), and 1°, 0°, and -1° at 71 000 ft (21.6 km). The initial throttle settings were unchanged until pull-up was initiated at which time power was reduced.

The push-over maneuver was initiated from a stabilized flight condition and consisted of control column forward until a normal acceleration of 0.5g was reached. This 0.5g condition was held for 10 sec, after which a recovery at a normal acceleration of 1.5g was made. Initial stabilized flight-path angles and altitudes investigated were 11° and 0° at 10 000 ft (3.0 km), 9° and 0° at 30 000 ft (9.1 km), 3° and 0° at 50 000 ft (15.2 km), and 1° and 0° at 71 000 ft (21.6 km). The run was terminated upon reaching level flight. Throttle position was not changed during the maneuver.

In the longitudinal trim runaway maneuvers, nose-down pitch-trim inputs representative of a runaway trim system were activated. The maximum trim deflection was limited to 10°; a value which the pilot could overcome by control column movement. There was a 3-sec delay between initiation of trim runaway and beginning of recovery by the pilot. In all cases the longitudinal control recovery capability with runaway trim was sufficient to allow recovery at a normal acceleration of 1.5g. For the maximum afterburner thrust setting cases, thrust was reduced after the recovery was begun.

The abandon maneuver used consisted of a release of the aircraft controls for a period of 20 sec from a 45° banked attitude with the airplane trim unchanged from the level-flight condition. At the end of this period, recovery to the level-flight condition was effected with normal acceleration limited to 1.5g and without change in thrust settings. This maneuver was used to represent the possible overspeeding effects arising from a lateral mistrim condition such as could be caused by autopilot malfunction which was not noticed until the airplane was falling off on one wing. The tests were made with pitch, yaw, and roll dampers both operative and inoperative.

Thrust Mismanagement Tests

Tunneling operations.- Tests were made to simulate the effects of mismanagement of thrust during the leveling maneuver at low altitudes required in observing established altitude restrictions in climbout. The altitude restrictions used were typical of those required of departing traffic in tunneling under landing traffic or traffic overflying the terminal area. The tests were started at the beginning of the take-off with either a minimum afterburning or maximum unaugmented power setting. Following take-off, the simulated airplane was climbed at speeds above V_2 speed. The airplane was leveled at 2500 ft (762 m), but power reduction was delayed until 3 sec after the sounding of the aural overspeed warning at 6 knots above V_{MO}. For one test, power reduction was made at 1500-ft (457 m) altitude in preparation for a leveling maneuver at 2500 ft in an attempt at proper thrust management.

Step-climb operations.- The effects of mismanagement of thrust in leveling maneuvers simulating response to altitude restrictions imposed by air traffic controllers during climbout were studied. Such maneuvers are utilized in altitude separation of climbing and descending traffic and in crossing of airways. The test was initiated in climbing flight 5000 ft (1.5 km) below the designated level-off altitude at the proper climb weight and with climb thrust. Minimum afterburner thrust was used below 25 000 ft (7.6 km) and maximum afterburner thrust was used above 25 000 ft. The climb was performed at constant indicated airspeed corresponding to V_{MO} until the leveling maneuver was initiated. Normal acceleration was held at about 0.8g (-0.2g incremental) during transition to level flight. Climb thrust was not reduced until after level flight was attained.

Operations in the ATC System

The climbouts and descents made during simulated operations in the ATC system included the crew workload of ATC communications and radar vectoring and navigation along the airways system. Low-altitude tunneling operations were required in some of the climbouts but no step-climb operations were requested by the controllers. The airplane was scheduled to be operated at not over 200 knots during maneuvering following take-off and then at 325 knots during climb to 11 000 ft (3.4 km). Beginning at 11 000 ft, vertical-flight-path guidance was provided by the command bar of the flight director indicator, programed to display the pitch-trim input required to return to the Mach number altitude schedule. A description of the vertical flight-path guidance system which was used in mechanizing the pitch command bar is presented in the appendix. This guidance was followed until approaching cruise conditions. The Mach number indicator and the altimeter were used to establish cruise conditions. With the exception of power reductions for low-altitude maneuvering, minimum afterburning thrust was used up to 31 000 ft (9.4 km). Above 31 000 ft, maximum afterburning thrust was used until approaching cruise conditions, at which time thrust was manually reduced to cruise thrust setting.

The descents were made by using the airspeed meter for speed guidance. The normal thrust setting was the engine idling condition until power was applied for level flight at the holding altitude (11 000 ft (3.4 km)) and holding airspeed (250 knots). In-flight thrust reversal below a Mach number of 1.2 and gear extension below a Mach number of 0.9 were available for flight-path control. (See table I.)

RESULTS AND DISCUSSION

Upset Maneuver

The results of the upset maneuver tests are presented in figure 4. The initial condition on the V_{MO} curve from which the upset was initiated and the maximum excursion in airspeed are shown for each test. Also shown is the calculated V_D curve. The results include upsets from level, climb, and descending flight conditions. Results are shown for both "hands off" tests and "hands on" tests. In the "hands off" tests, the aircraft tended to a partial recovery; the recovery was completed by the pilot at the end of 20 sec. For the "hands on" tests, increasing forward control column deflection was used during the 20 sec to hold the upset flight path. The results in figure 4 show that, as indicated by the calculated curve, the overspeeding and altitude loss due to the upset maneuvers is greatest for the higher speed, higher altitude conditions. For 71 000-ft (21.6 km) altitude, overspeeds on the order of 150 to 160 knots for the "hands on" case were measured. For the "hands off" case, natural recovery accelerations were as much as 0.3g and tended to reduce the overspeeding by as much as 40 to 50 knots.

For the lower speed and altitude initial conditions, the speed and altitude excursions tended to be smaller and the difference between the "hands on" and "hands off" cases also tended to be smaller.

The change in initial flight-path angle from which the 7.5° upset was measured resulted mainly in an effect on altitude excursion and less effect on airspeed excursion. For 71 000-ft (21.6 km) altitude, a change of -1° in initial flight-path angle resulted generally in an increase in altitude excursion on the order of 1500-ft (457 m) altitude but no increase in airspeed. For 30 000-ft (9.1 km) altitude, a change in the initial flight-path angle of -6.5° resulted in an increase in altitude excursion of 2200 to 3500 ft (0.7 to 1.1 km) and an increase in airspeed of 15 to 25 knots.

The data of figure 4 show that the altitude and airspeed excursions from the descending initial conditions agree fairly well with the calculated data which established the design dive speed V_D curve.

Analysis of data.- In general, the large overspeeds in the indicated airspeed at the higher speed, high altitude conditions are principally the result of a large loss in altitude and, hence, increase in air density and are not associated with an increase in true speed. The altitude lost, however, is a direct function of flight-path angle, true speed, and recovery or level-off time. For supersonic cruise (500 KIAS and 71 000-ft (21.6 km) altitude), the loss in altitude in the 20-sec dive part of the upset maneuver can be shown by calculation to be about 7600 ft (2.3 km) or slightly over 3.5 times the loss in altitude for a subsonic cruise case of $M = 0.8$ and 30 000-ft (9.1 km) altitude. Also, the increase in recovery times and subsequent loss of altitude likewise increases greatly at supersonic speeds. For this subsonic case, the recovery time is 6 to 7 sec and the altitude loss is 330 ft (100 m). For 500 KIAS and 71 000-ft altitude, the recovery time is 24 sec and the altitude lost is 4500 ft (1.4 km). Although the changes in IAS in the upsets were large, especially for supersonic condition, the increases in true airspeed and, hence, Mach number were small, less than 60 knots (0.1M) for all upsets from level-flight conditions. It was evident in the supersonic cases that, during the upsets, the thrust increased faster than the drag in contrast with the subsonic cases. This increase in thrust over drag, however, accounted for less than 10 knots of the maximum 60 knots increase in true speed.

7.5° entry and recovery.- It is important to note that the altitude loss which is shown in figure 4 does not include altitude that would be lost getting into the 7.5° upset conditions. The additional altitude lost for a 0.5g normal acceleration entry into this upset would be approximately the same as the altitude lost in recovery (4500 ft (1.4 km)). Therefore, the total altitude lost in setting up and executing a 7.5° upset at 500 KIAS and 71 000-ft (21.6 km) altitude would be a minimum of 16 000 to 17 000 ft (4.9 to 5.2 km). Also, the overspeed excursion in KIAS would be of the order of 70 knots greater than the overspeed excursion shown. It is also important to note that, for a 0.5g normal acceleration maneuver, the time required to get into a 7.5° upset condition for the supersonic cruise case is 24 sec, a time longer than the 20-sec specified time in the upset condition, whereas the time required to get into the upset condition for the subsonic case is only 6 to 7 sec. However, if entry into the upset condition is at higher maneuver accelerations, then entry times will be correspondingly shorter.

In consideration of the greatly increased time required to get into a 7.5° upset for a given maneuver acceleration at cruise conditions in contrast with subsonic operations, the extension of the upset maneuver specified for subsonic operations to the supersonic case appears subject to some question. Further, the pilots criticized the maneuver as unrealistic since the aircraft which was simulated in these tests had to be held in the 7.5° dive by forward stick movement because of its natural recovery tendency.

Push-Over Maneuver

The results of the 0.5g push-over tests from the V_{MO} curve are presented in figure 5. Results are shown for push-overs from level flight and from accelerating climbing flight. The maneuver accelerations rarely varied more than ±0.05g from the specified values. The length of run time, which included a 10-sec pitch-over time and a 10-sec recovery time, generally required 28 to 30 sec. The pilot required 4 to 5 sec to establish a specified g level.

For the majority of cases, the airspeed excursion was considerably less than the speed margin shown. It can be seen in figure 5, however, that the speed excursion was greater at the lower speed, lower altitude initial conditions. For the 335 KIAS, 10 000-ft (3.0 km) altitude initial condition, the speed excursion was slightly greater than the speed margin shown. The larger speed excursion for the lower speed conditions would be expected, since, for this type of maneuver, the airspeed excursion is a function of the magnitude of angle of pitch-over and, for a specific maneuver acceleration, the length of time. The pitch angle reached is inversely related to the true velocity. For example, at 335 KIAS and 10 000-ft altitude, the pitch-angle excursion for a 0.5g push-over for 10 sec is -16°. For the initial conditions of level flight and trimmed thrust, this results in a Mach number excursion of 0.11 which corresponds to an IAS excursion of 88 knots. For 500 KIAS, 71 000-ft (21.6 km) altitude, level-flight initial condition, the pitch-angle excursion is -4.5°, the Mach number excursion is 0.04, and the corresponding IAS excursion is 33 knots.

The altitude excursions for the push-over from level flight ranged from 3000 ft to 4000 ft (0.9 to 1.2 km) in all cases. This small variation in altitude loss would be expected since the altitude loss in this type of maneuver is basically a function of only the maneuver acceleration and the maneuver time squared. For the push-overs from the climb condition at the low altitude, the altitude at the end of the run was higher than the altitude at the beginning of the run. At the higher altitude initial conditions with smaller climb angles, the converse is true.

The constant-acceleration push-over maneuver may provide a more rational criterion in determining speed margins for the SST than the presently used 7.5° upset maneuver because the entry time is an integral part of the maneuver. Furthermore, control-system failures which result in driving all or part of the control surfaces against stops, thus producing step inputs, tend to result in constant acceleration maneuvers. It is suggested that the value of acceleration to be used at each speed should reflect the control and structural characteristics of the airplane. In addition, the maneuver time specified should be sufficient to include recognition of the situation by the pilot and his reaction to it.

Longitudinal Trim Runaway Maneuver

During initial trim runaway maneuver tests at supersonic speeds using the nominal 0.5°/sec elevator deflection rate, with the elevator deflection limited to 10°, the altitude excursions were less than 100 ft (30 m) and the airspeed excursions could hardly be noticed. The disturbance required only a slight corrective effort by the pilot. For later tests, the elevator rate was increased so that the normal acceleration attained when the pilot initiated recovery 3 sec later was 0.5g to 0.6g (0.5g to 0.4g incremental) with dampers on the 0.2g to 0.3g (0.8g to 0.7g incremental) with dampers off.

Even for the increased elevator rates, recoveries were not difficult for pitch dampers on but 10 to 20 sec were required for the pilot to reestablish level flight (fig. 6). Trim runaway recoveries were also made with the pitch damper off because it was felt that a malfunctioning trim system may well render the damper inoperative. With dampers off, the pilot had a much harder job controlling the airplane and would frequently overcontrol resulting in large acceleration excursions (fig. 6). This difficulty in control resulted in slightly larger time to bring the aircraft back under control, with the result that the overspeeding was slightly greater than for dampers on. Because of the absence of acceleration forces on the pilot it is felt that the recovery task was probably more difficult in the fixed-base simulator than would be the case under actual flight conditions. On the other hand, it is also felt that in the simulator the pilot is under a lot less strain than in actual flight conditions so that the control is possibly smoother.

The overspeed results of the trim runaway tests with the increased elevator rates are given in figure 7. Results are given for three supersonic cases and one subsonic case and for initial thrust conditions of trimmed thrust and maximum afterburning. Throttle back to approximately trim thrust during recovery was made for the maximum afterburner cases. The results show that the altitude losses were less than 500 ft (152 m). These small altitude losses are apparently associated with the short time lapse (3 sec) before recovery is initiated.

The airspeed excursions were found to be highly dependent on the initial thrust condition. For the trimmed thrust condition, speed excursions were only 10 to 15 knots. For the maximum afterburner thrust condition which might represent the case of a trim runaway occurring before power reduction was accomplished after a level-off from climb, the speed excursions were a maximum of 34 knots. The speed excursions measured in the trim runaway maneuvers were all considerably less than the speed margin provided by the upset maneuver criterion.

Abandon Maneuver

The results of 45° abandon maneuvers are presented in figure 8. Three initial conditions were investigated, one at subsonic speeds and two at supersonic speeds. Various combinations of lateral, directional, and longitudinal damping augmentation were used in the runs. There was a noticeable increase in altitude and airspeed excursion for the lower altitude initial condition for the case where pitch damping was on. For the 30 000-ft (9.1 km) altitude initial condition (pitch dampers on), the V_D boundary was exceeded by 15 to 25 KIAS. The pitch damper affects the airspeed and altitude excursions by opposing the tendency of the aircraft to pitch up in a turn because of the level-flight trim. This results in more pitch down with dampers on and, hence, greater airspeed-altitude excursions. An analysis of the aerodynamics particular to this problem shows that subsonically the pitch damper has greater effectiveness, in part, because of the low subsonic static stability margin. The variation of the airspeed excursions for pitch dampers on over the altitude regime appears quite similar to those measured in the 0.5g push-overs.

Thrust Mismanagement

Tunneling operations.- Time histories of pitch angle, rate of climb, excess thrust-weight ratio, and indicated airspeed obtained from the tunneling tests are presented in figure 9. Results of tests with minimum afterburning power setting (min A/B) and maximum nonafterburning power setting (max unaugmented) are given. The purpose of these tests was to study the overspeed potential of the SST immediately following take-off if proper thrust management is not used. Improper thrust management can arise under these circumstances due to the crew's high activity with such factors as ATC communications, navigation, and post-take-off check lists.

For both the minimum afterburner and maximum nonaugmented tests, throttle back was 3 sec after V_{MO} was reached at approximately 2500-ft (762 m) altitude. For the minimum afterburner case, the time from lift-off to throttle back was only about 1 min. Excess thrust-weight ratio was approximately 0.35, resulting in climb angles of 10° and acceleration rates of 0.12g. For the maximum nonaugmented case, the excess thrust-weight ratio of the SST was reduced to approximately 0.25 which resulted in an increase in time from lift-off to throttle back of approximately 30 sec. These tests showed overshoots of V_{MO} of 20 and 30 KIAS.

Although the overspeeding occurring in these tests amounted to only 20 and 30 knots above V_{MO}, it should be pointed out that, for the minimum afterburner case, the SST performance is such that a time delay in power reduction of only 15 sec after overspeed warning would result in exceedence of V_D.

Step-climb operations.- The results of the step-climb operations are presented in figure 10. These data show the overspeeding to fall within the speed margin provided by the 7.5° upset maneuver except for 6500-ft (2.0 km) altitude for which the airspeed excursion was approximately 100 KIAS. A reduction in speed excursion is observed with increase in altitude and is primarily due to the general reduction of excess thrust which occurs with an increase in altitude. At 68 000-ft (20.1 km) altitude, the speed excursion is only about 15 KIAS. It should be noted, however, that the overspeeding from a climb condition is also a function of the climb airspeed (climb angle). Calculations at climb airspeeds other than those used in the tests indicate that the values of overspeeding shown are near the peak values.

Operations in the ATC System

The overspeed excursions recorded in 44 departure and 31 arrival tests simulating operation in the ATC system are presented in figure 11. For both departures and arrivals, the overspeed events are shown as points of the maximum overspeed velocity reached at the altitude at which it occurred. The overspeeds generally occurred in the region where the climb or descent profile was close to the V_{MO} curve. The overspeeds in the departures were generally less than 25 knots. The overspeeds in arrivals were smaller, generally less than 15 knots, except for one overspeed of 40 knots at 19 000-ft (5.8 km) altitude. All of the overspeed excursions fell within the speed margin provided by the 7.5° upset maneuver. However, overspeeds in departures tended to approach the V_D boundary at 71 000-ft (21.6 km) altitude. This is the minimum boundary which is established by the "miscellaneous causes." In some cases, the overspeeds shown were probably less than might be expected in actual practice, since the pilots used normal acceleration maneuvers exceeding the passenger comfort level (1.2g) in the recovery from the developing overspeed conditions.

A pitch command steering mode was available on the flight director to provide guidance along the climb profile above 11 000 ft (3.4 km), and 47 percent of the overspeeds shown in this altitude region are associated with the problem of establishing the airplane on the climb profile. At altitudes from 24 000 to 30 500 ft (7.3 to 9.3 km), the two overspeeds shown are the result of power increase from minimum afterburner to maximum afterburner without sufficient increase in flight-path angle. The overspeeds in the 60 000- to 70 000-ft (18.3 to 21.3 km) region are about as frequent as at the lower altitudes and occur mostly in leveling off for cruise. In this region the speed margin begins to decrease and at 71 000 ft (21.6 km) is only about 30 knots.

For arrivals, overspeeds occur principally at the lower altitudes where the descent profile approaches the V_{MO} curve. The pilots preferred descent speeds higher than the prescribed 300 KIAS and tended to approach the V_{MO} curve below 40 000-ft (12.2 km) altitude. The magnitude and number of overspeeds were relatively less than on departure runs. The one overspeed excursion shown at 71 000 ft (21.6 km) occurred during a push-over to initiate a rapid descent.

The pilots commented that they had considerable difficulty in controlling airspeed. They felt that in an actual airplane the airspeed oscillations would be somewhat less because of the airplane acceleration cues which act as lead information and are provided by the airplane. On the other hand, in actual flight, air turbulence can create cockpit vibrations to the extent that instrument-reading errors occur and might lead to larger airspeed excursions than found in the simulator. At the higher speeds, more precise attitude information than that provided by the conventional attitude gyro is needed to help reduce airspeed oscillations. The pilots concluded that, in order to avoid overspeeding frequently, it would be necessary to fly from 10 to 20 knots below V_{MO}. The higher value of reduction in operating speed would especially be necessary in cases where maneuvering flight was required.

CONCLUDING REMARKS

Using a fixed-base piloted aircraft simulator, a preliminary investigation has been made of airspeed increases for specific maneuvers such as: (1) upsets in pitch; (2) push-overs at a normal acceleration of 1/2g; (3) longitudinal trim runaways; (4) abandons of control in a 45° bank; and (5) thrust mismanagement in level offs from climbouts (for both tunneling operations following take-off and step climbs at higher altitudes) and for simulated operations in the ATC system. The characteristics of a generalized double-delta SST configuration were used in the simulation. The experimentally determined airspeed excursions were compared with a speed margin calculated for a 7.5° upset maneuver as one of the criteria currently specified by the Federal Aviation Regulations.

The measured airspeed and altitude excursions from a 7.5° upset maneuver agreed with the calculated values. The airspeed and altitude excursions from additional maneuvers – such as, 1/2g, 10-sec push-over; longitudinal trim runaway; 45°, 20-sec abandon; and level off from climb – were much less than the airspeed and altitude excursions from the 7.5° upset maneuver at supersonic speeds. However, at low subsonic speeds the speed margin established by the 7.5° upset maneuver was slightly exceeded by speed excursions from maneuvers such as 1/2g, 10-sec push-over; 45°, 20-sec abandon (all damping augmentation on); and level off from climb.

The time required to enter into the 7.5° upset maneuver (which was not considered in determining the speed margin) for the SST at cruise speed is four times as great as that for the subsonic jet transport at cruise speed for the same maneuver acceleration. These longer entry times which are available for corrective action make the 7.5° upset maneuver appear to be inappropriate for the SST at supersonic speeds. The constant-acceleration push-over type of maneuver which includes entry as an integral part of the maneuver, possibly provides a more rational maneuver for determining speed margins at supersonic speeds.

Operations in the ATC system resulted in overspeeds particularly where the ascent and descent profiles were adjacent to the maximum operating limit speed. Overspeeds were generally small, but still tended to approach the design dive speed at the minimum boundary established by the "miscellaneous causes" provision at 71 000-ft (21.6 km) altitude. The pilots recommended that in order to avoid frequent overspeeds the climb profile should be backed away from the maximum operating limit speed by 10 to 20 knots.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., November 3, 1966,
720-04-00-05-23.

APPENDIX

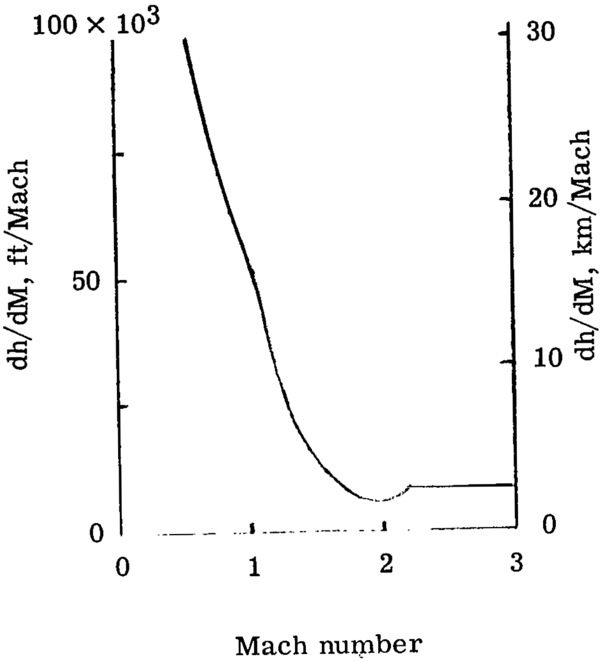
FLIGHT DIRECTOR VERTICAL FLIGHT-PATH COMMAND PROGRAM

The command bar of the flight director was programed for the climb profile with the following equation:

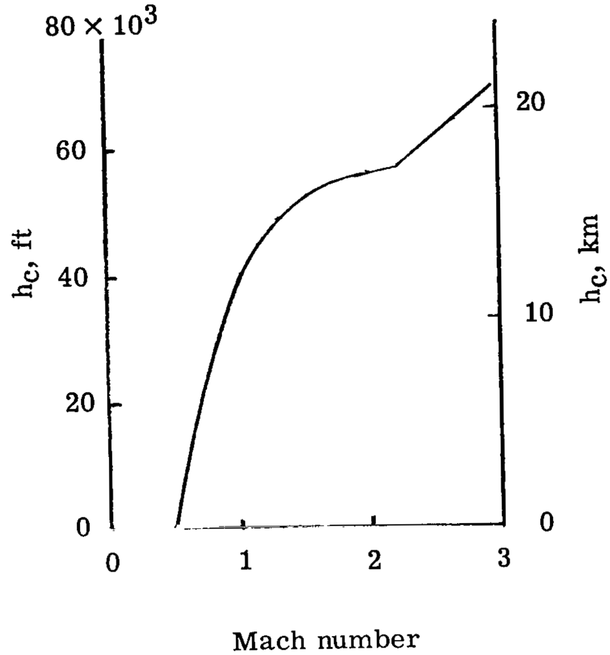
$$\epsilon = K_1\left(\dot{h}_c - \dot{h}_o\right) + K_2(1 + 0.006t)\left(h_c - h_o\right) - K_3\Delta\theta$$

where

ϵ	command pitch bar deflection, deg
K_1	command pitch bar deflection per rate of climb error, 0.0768 deg/ft/sec (0.0252 deg/m/sec)
K_2	command pitch bar deflection per altitude error, 0.00426 deg/ft (0.0140 deg/m)
0.006t	integration factor
K_3	command pitch bar deflection per pitch angle, 195 deg/rad
$\dot{h}_c$	command rate of climb, $\frac{dh}{dM}\frac{dM}{dt}$, ft/sec (m/sec)
$\frac{dh}{dM} = f(M)$	(see sketch 1)
$\dot{h}_o$	rate of climb, ft/sec (m/sec)
h_c	command altitude, f(M) (see sketch 2)
h_o	altitude, ft
$\Delta\theta$	change in aircraft pitch angle, rad



Sketch 1



Sketch 2

REFERENCES

1. Anon.: Maximum Operating Limit Speed. Airworthiness Standards: Transport Category Airplanes. Federal Aviation Regulation Part 25.1505, Rules Service Co. (Washington, D.C.), Feb. 1, 1965.
2. Sawyer, Richard H.; Stickle, Joseph W.; and Morris, Richard: A Simulator Study of the Supersonic Transport in the Air Traffic Control System. 1964 Proceedings National Aerospace Electronics Conference, IEEE, May 1964, pp. 352-356.
3. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Flight Standards Service, FAA, Nov. 1, 1965.
4. Anon.: Tentative Airworthiness Standards for Supersonic Transports. Revision 2. Flight Standards Service, FAA, Dec. 30, 1966.

TABLE I.- SST CHARACTERISTICS

V_{MO}, knots	335	350	450	500
h, ft	10 000	30 000	50 000	71 000
(km)	(3.05)	(9.15)	(15.24)	(21.62)
$\frac{T - D}{W}$	0.26 (min. A/B)	0.25 (max. A/B)	0.13 (max. A/B)	0.12 (max. A/B)
Longitudinal short period,[a] sec	[b]31	[b]31	11	5
Cycles to half-amplitude[a]	0.07	0.09	0.14	0.26
$t_{1/2}$ (spiral),[c] sec	14	11	10	15
$t_{1/2}$ (spiral), sec	9	7	24	130
Δa_x (landing gear extend), g units	0.11	0.11	----------	----------
Δa_x (reverse thrust), g units	0.15	0.12	----------	----------

[a]Rate damping augmentation on.

[b]Over critically damped.

[c]Yaw and roll rate damping augmentation on.

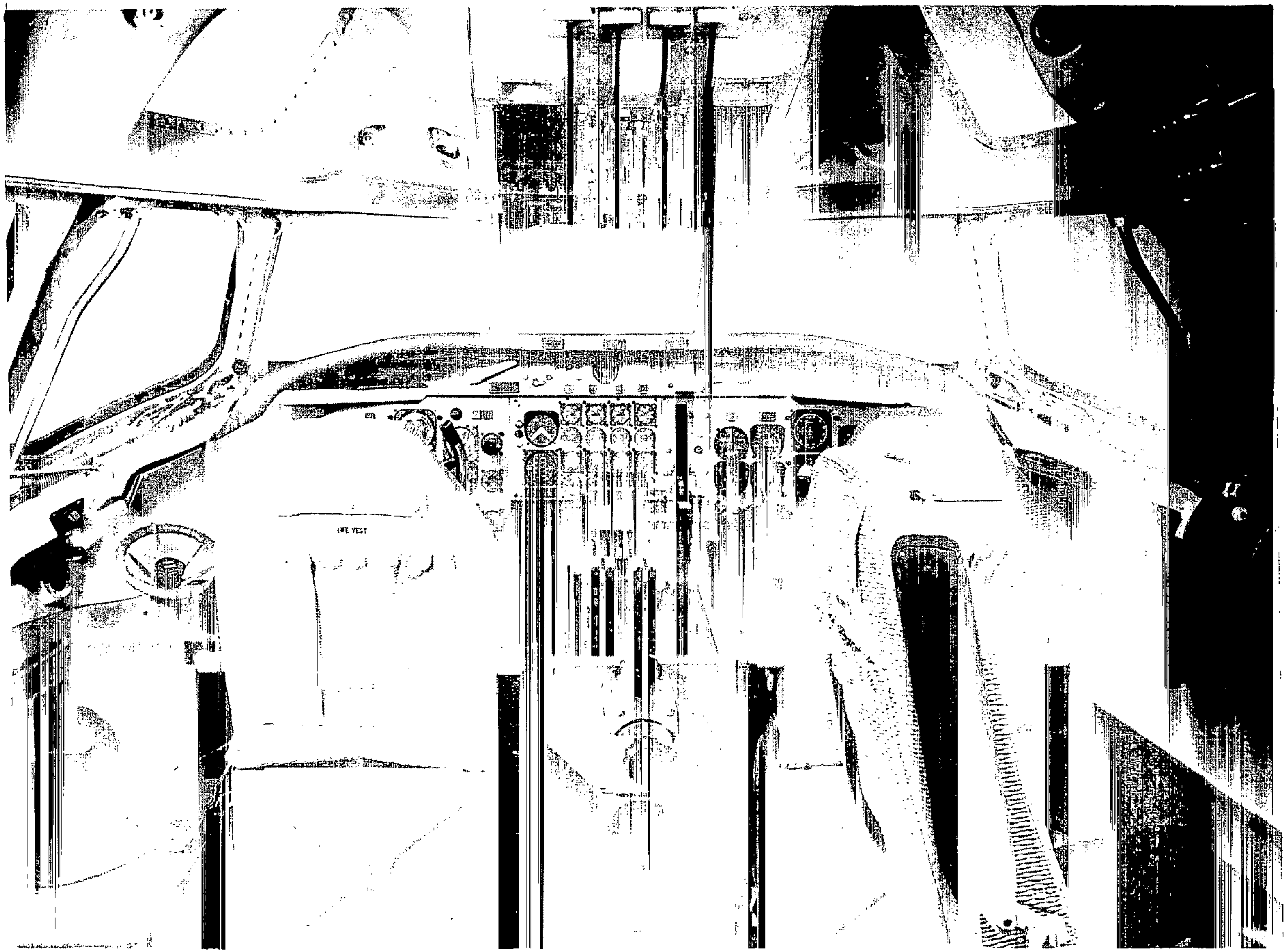


Figure 1.- Interior view of the fixed-base SST simulator cockpit. L-64-1743

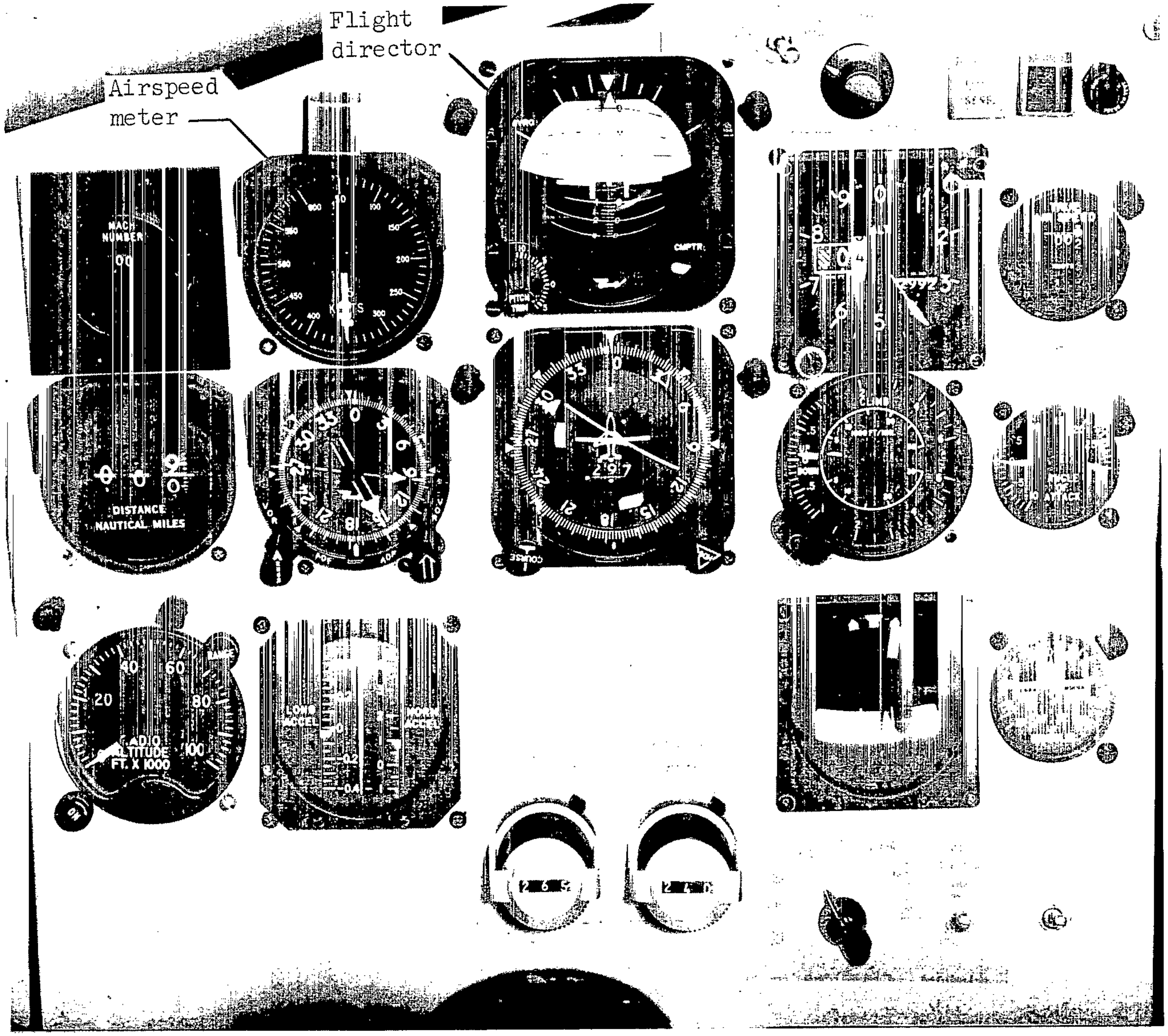


Figure 2.- View of the captain's panel showing flight instruments used. L-65-9199.1

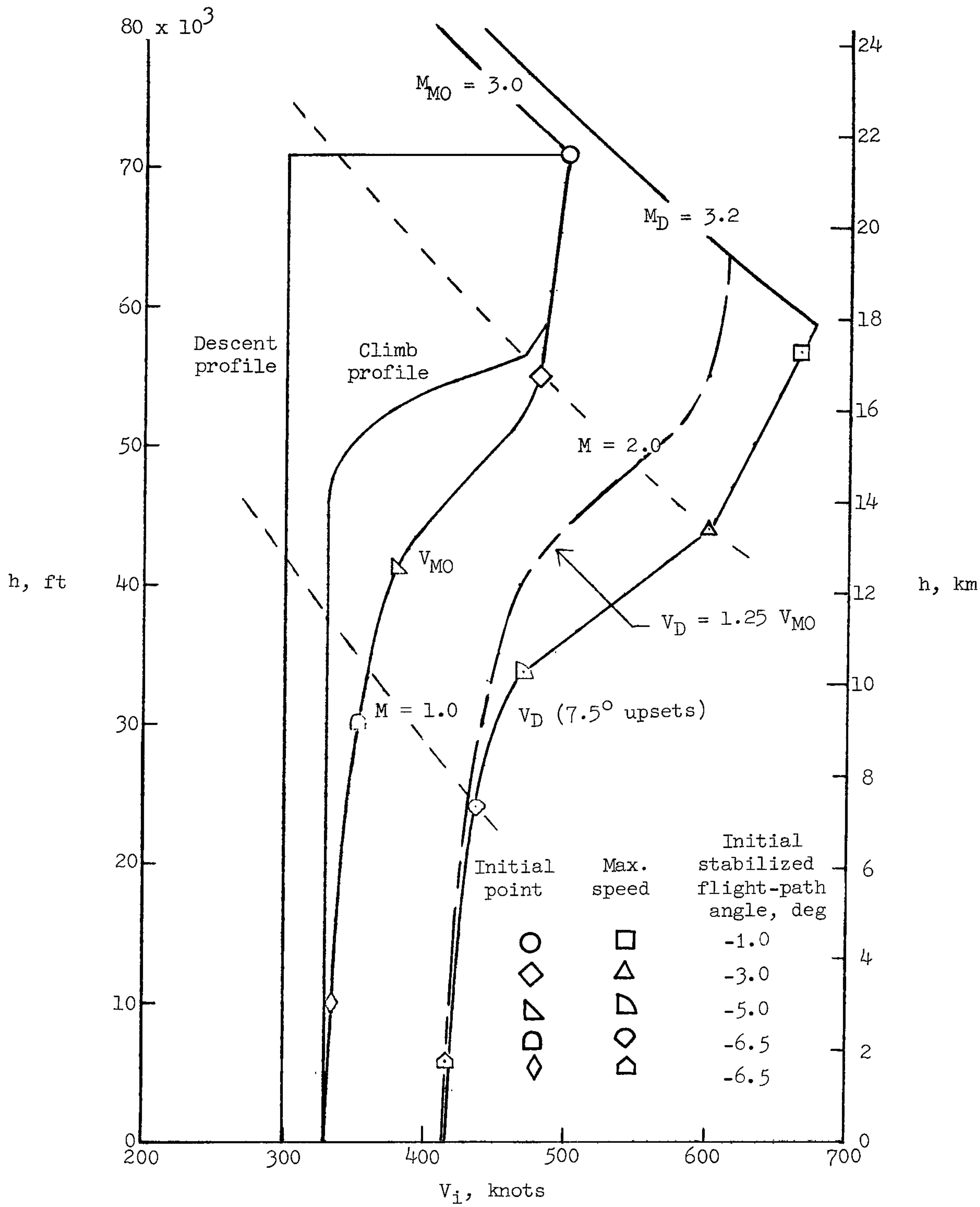


Figure 3.- Speed margin above V_{MO} as determined by calculations for a 7.5° upset from initial stabilized descent flight path and idle thrust. Also shown are climb and descent profiles and curves of airspeed and altitude for $M = 1.0$ and 2.0.

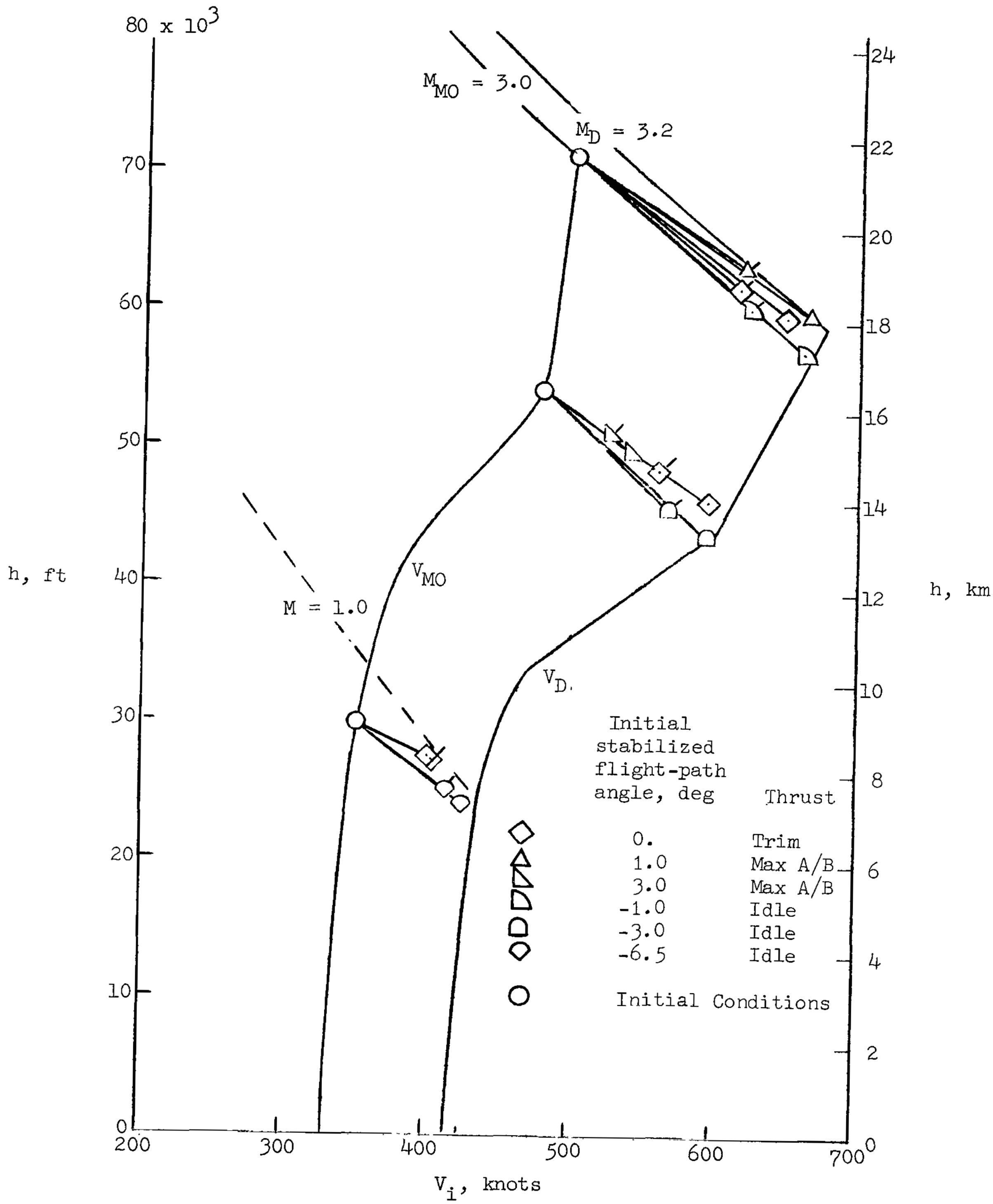


Figure 4.- Airspeed and altitude excursions for 7.5° upsets from initial stabilized climb, level, and descent flight paths on the V_{MO} curve. Ticked symbols denote hands off longitudinal control until recovery.

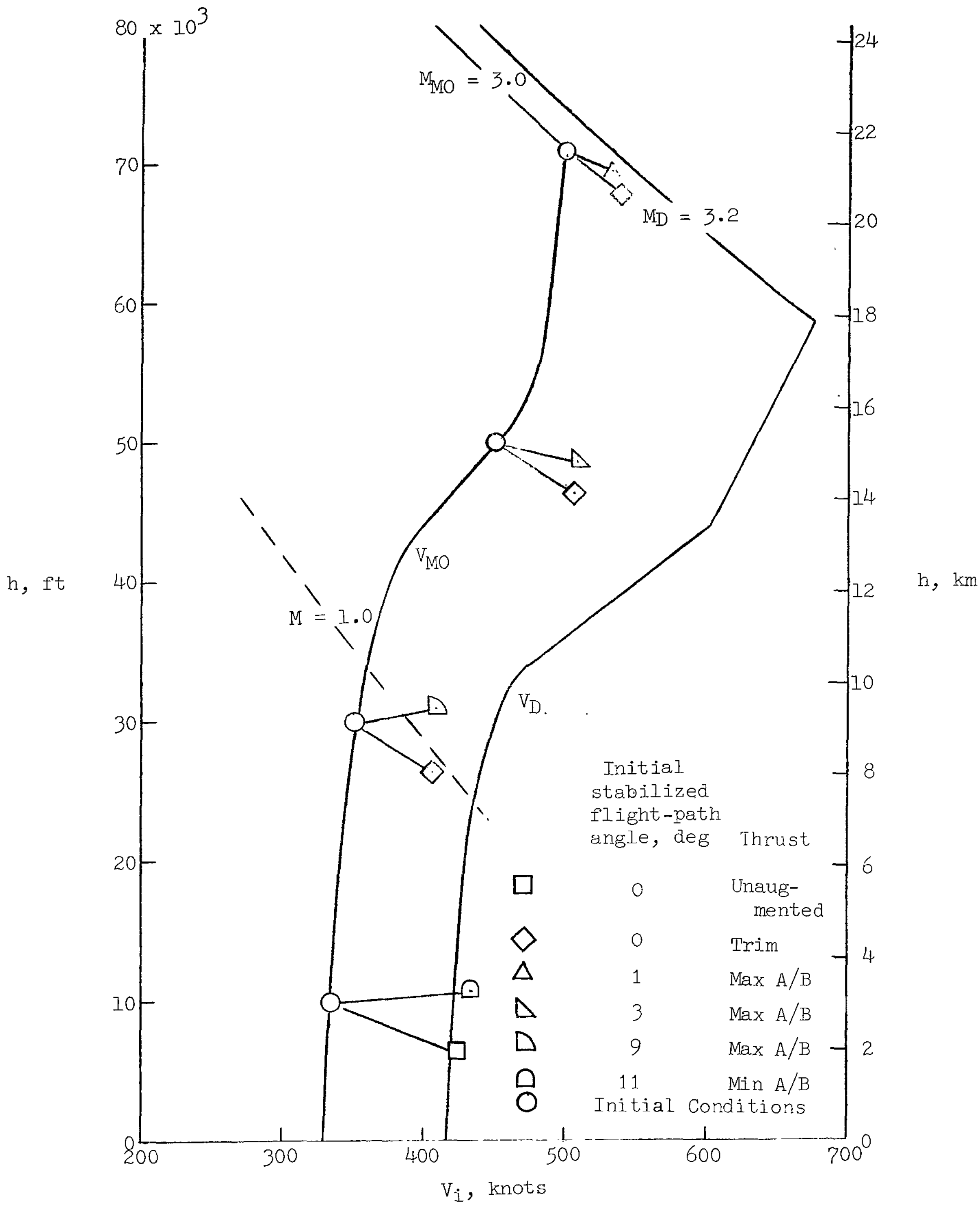


Figure 5.- Airspeed and altitude excursions for 1/2g, 10-sec push-overs from stabilized climbing and level conditions.

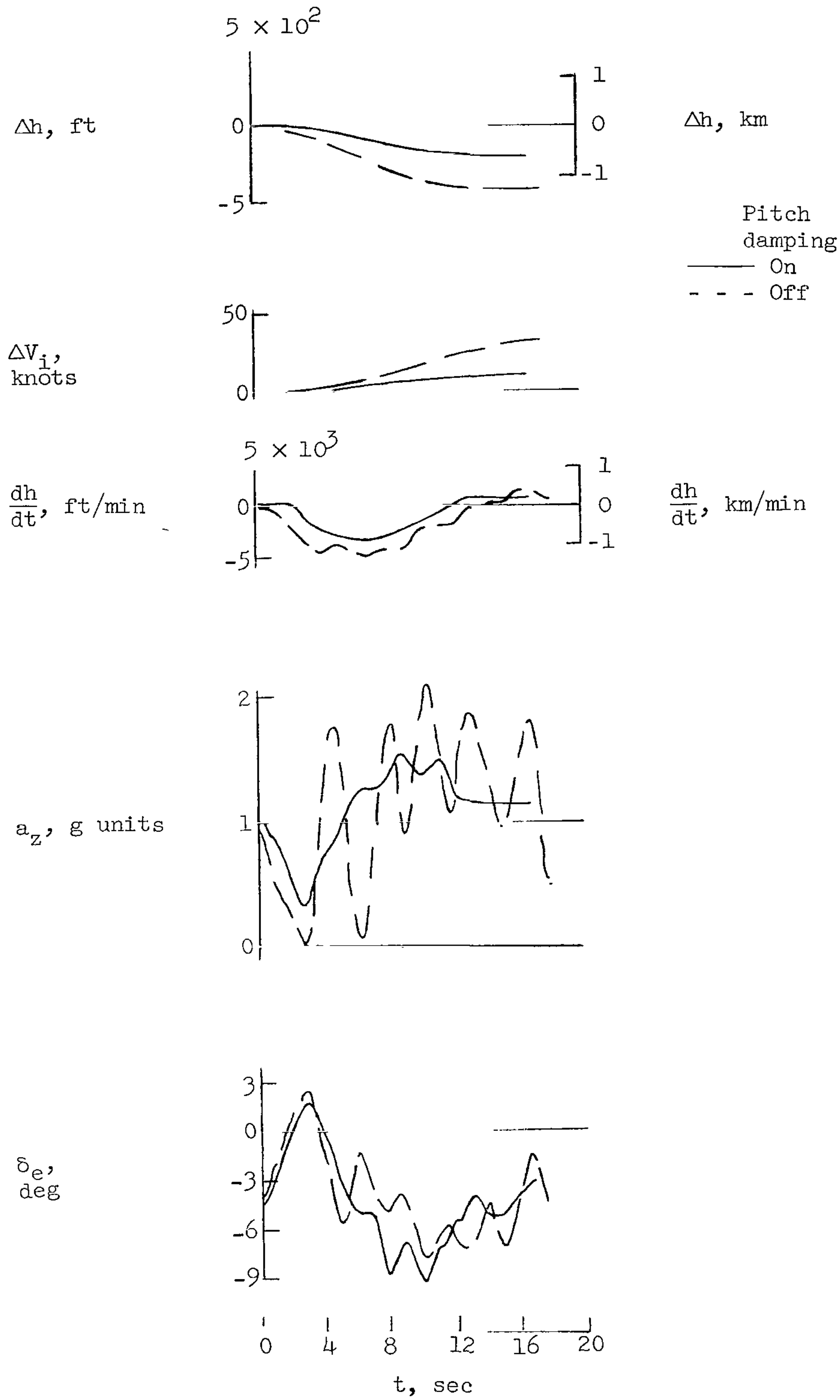


Figure 6.- Time histories of quantities measured during two longitudinal trim runaways at $M = 1.2$ and 41 000-ft (12.5 km) altitude.

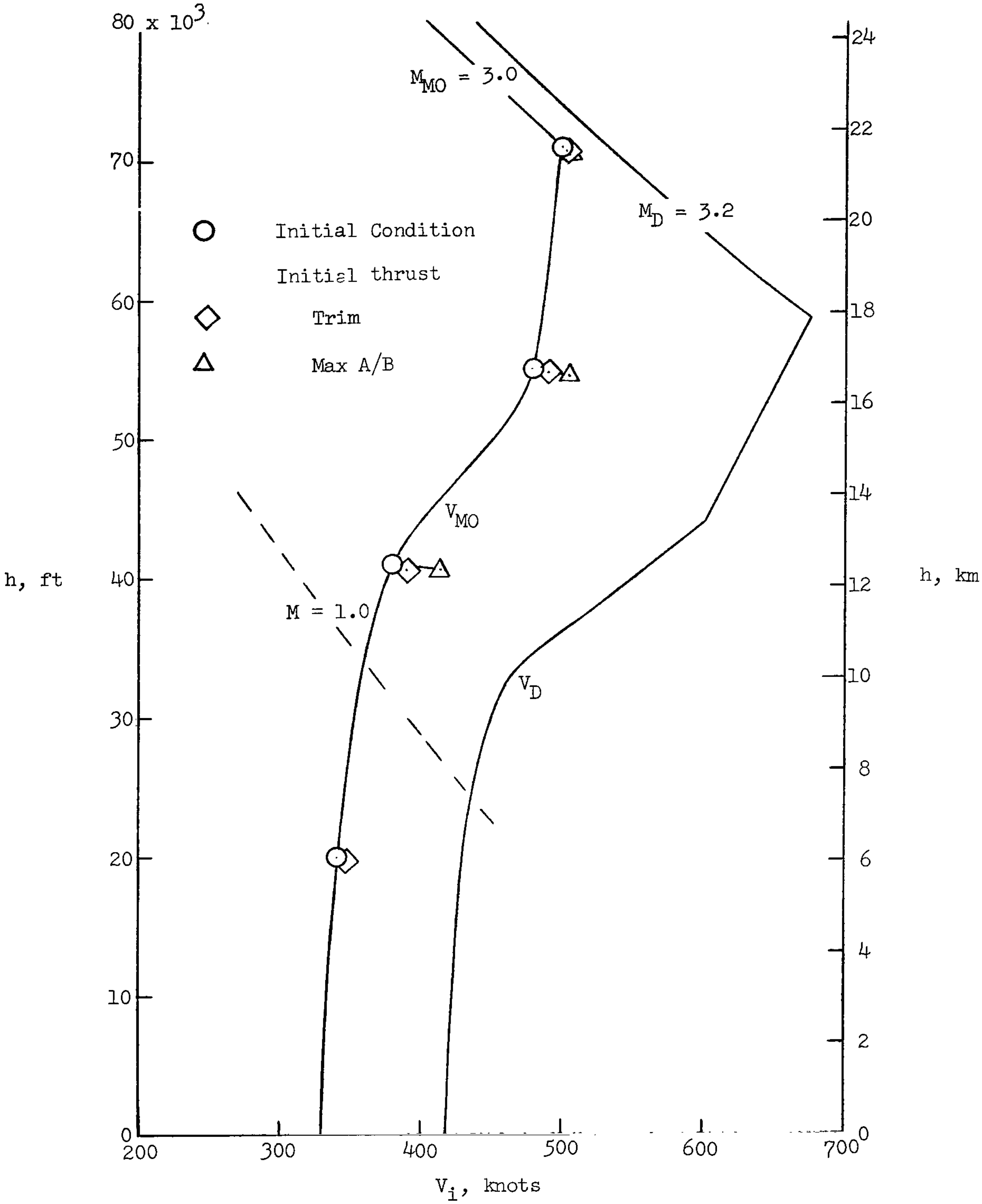


Figure 7.- Airspeed and altitude excursions for longitudinal trim runaway maneuvers, pitch damping off, with both initial trim thrust and maximum A/B thrust.

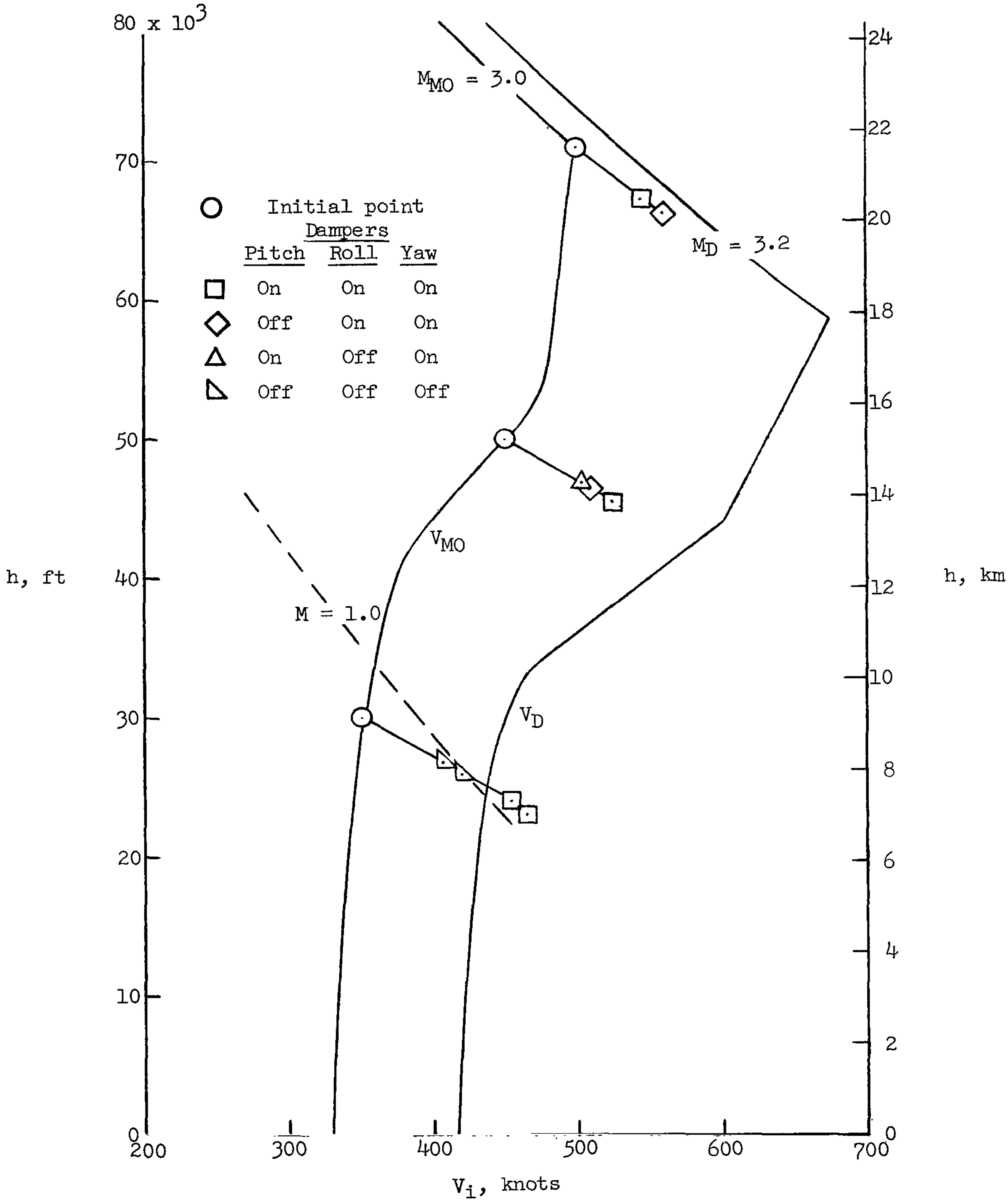


Figure 8.- Airspeed and altitude excursions from a 45^0 banked 20-sec abandon maneuver.

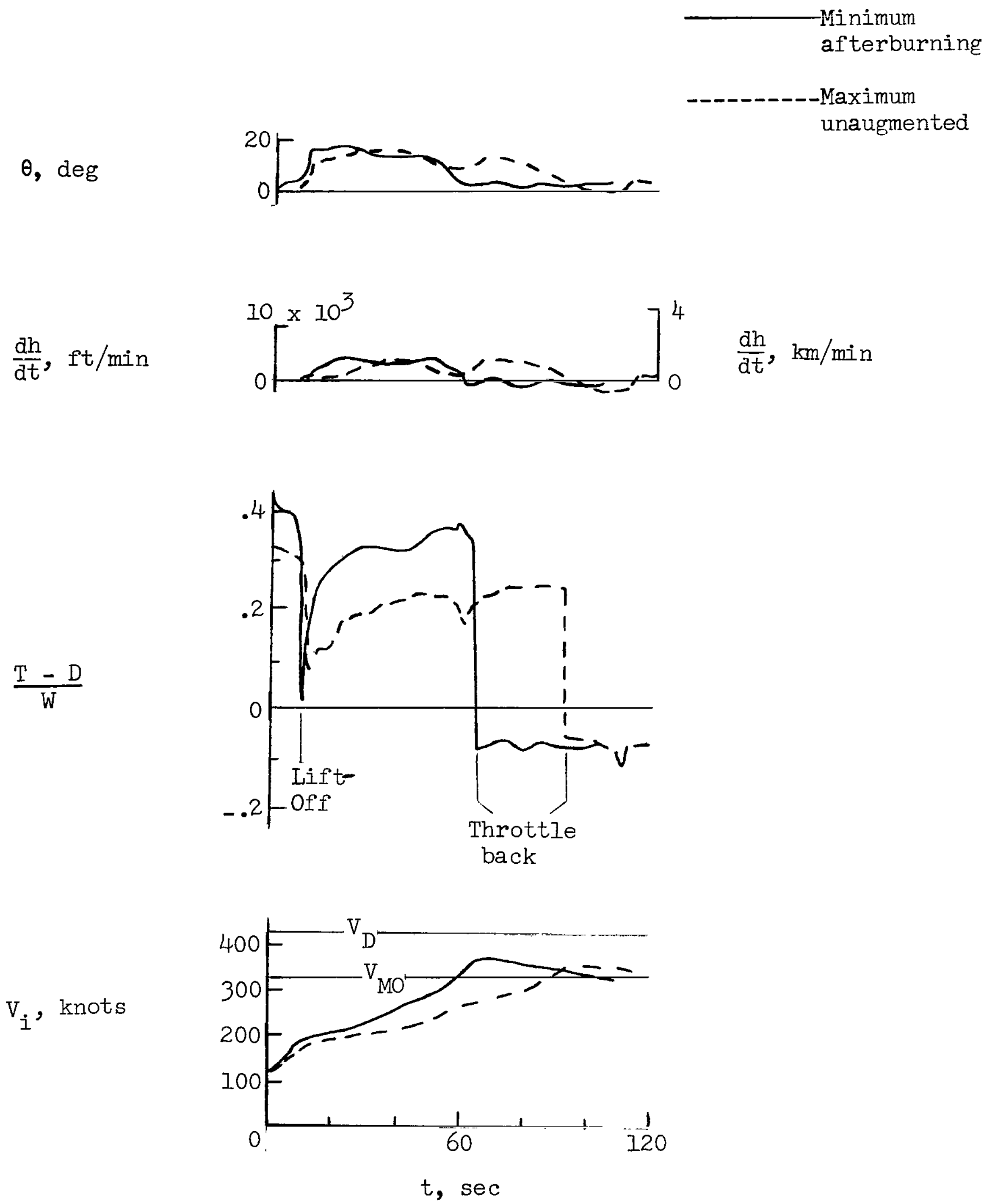


Figure 9.- Time histories of quantities measured in a minimum afterburner thrust and a maximum nonaugmented thrust take-off.

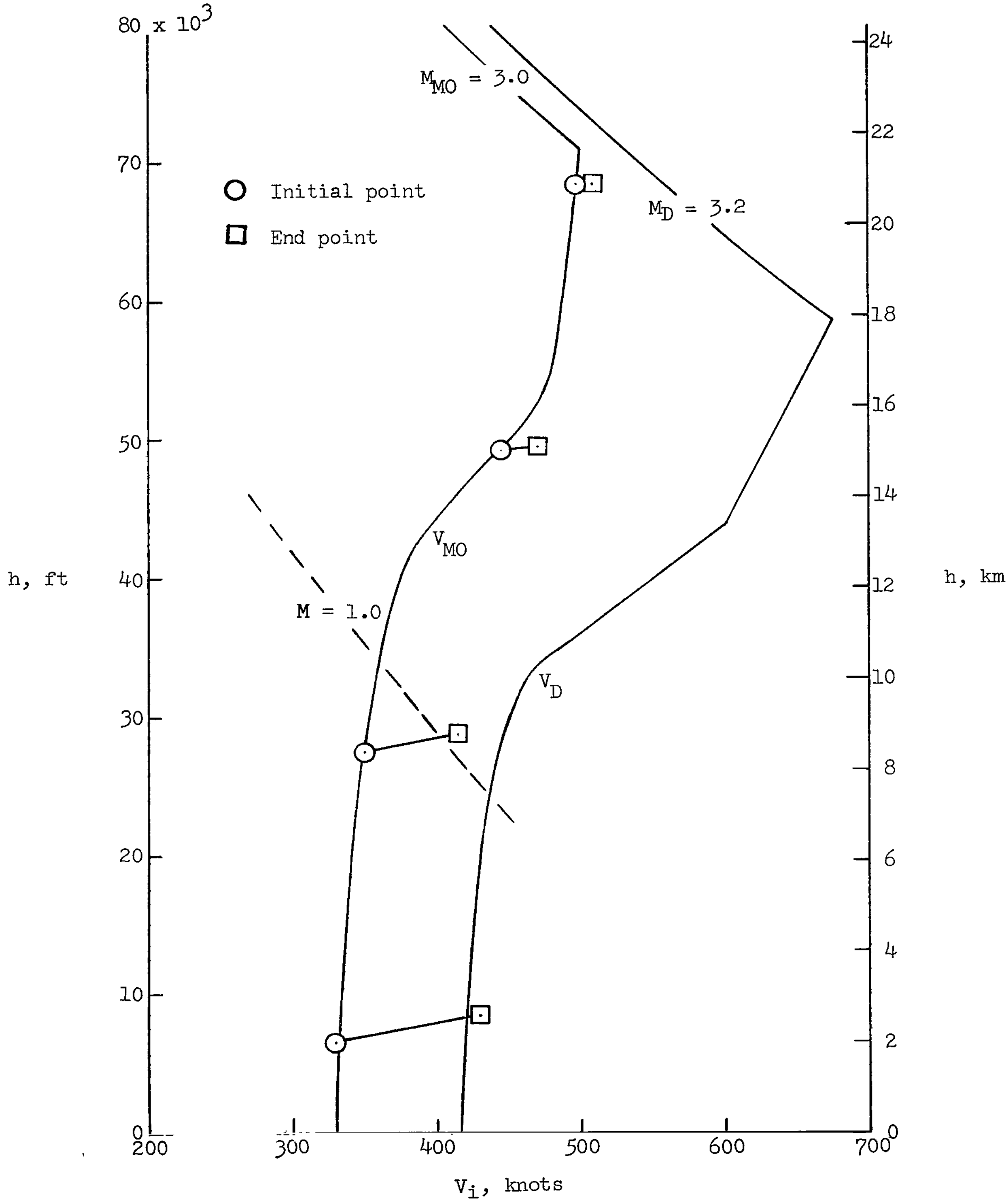
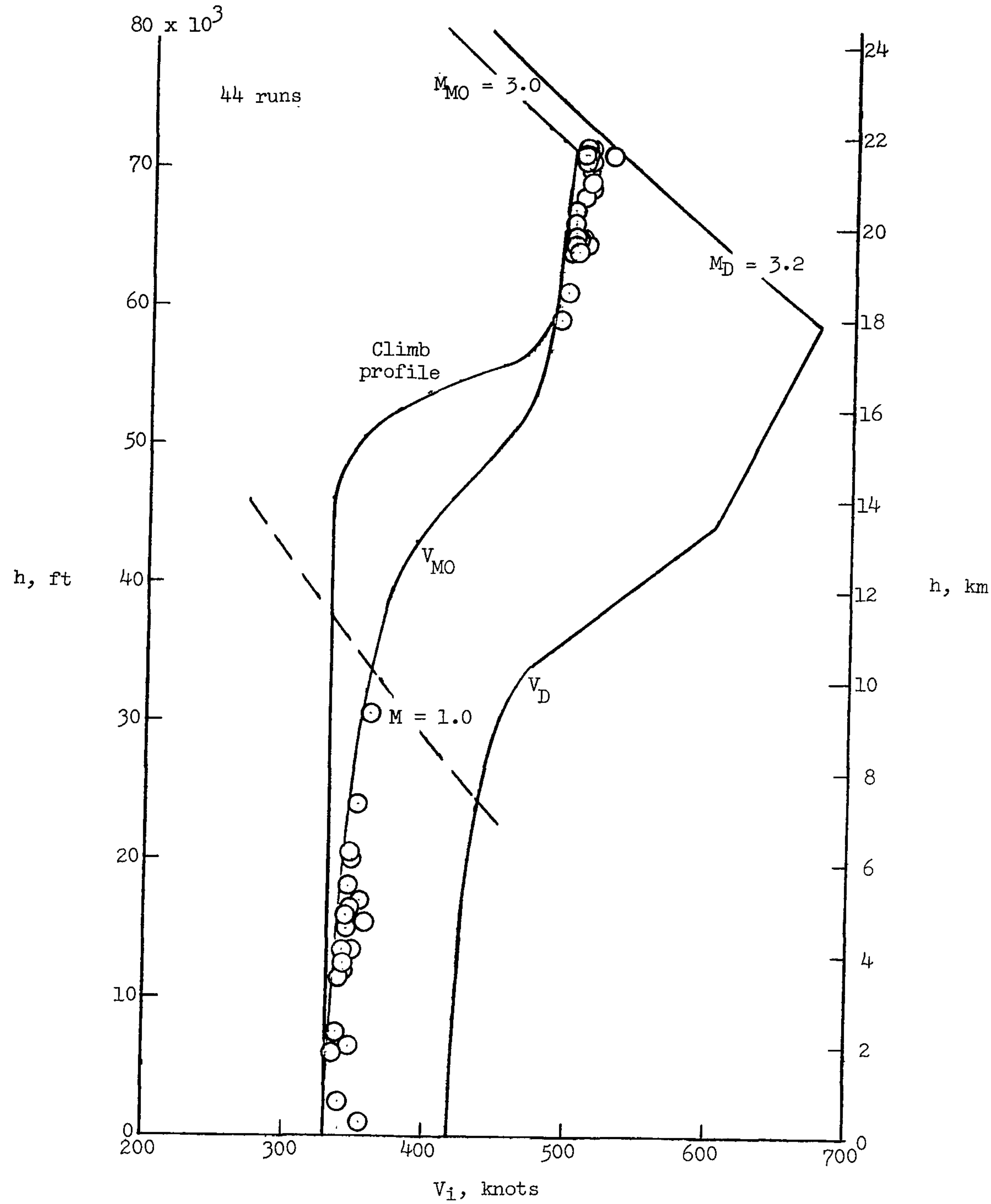
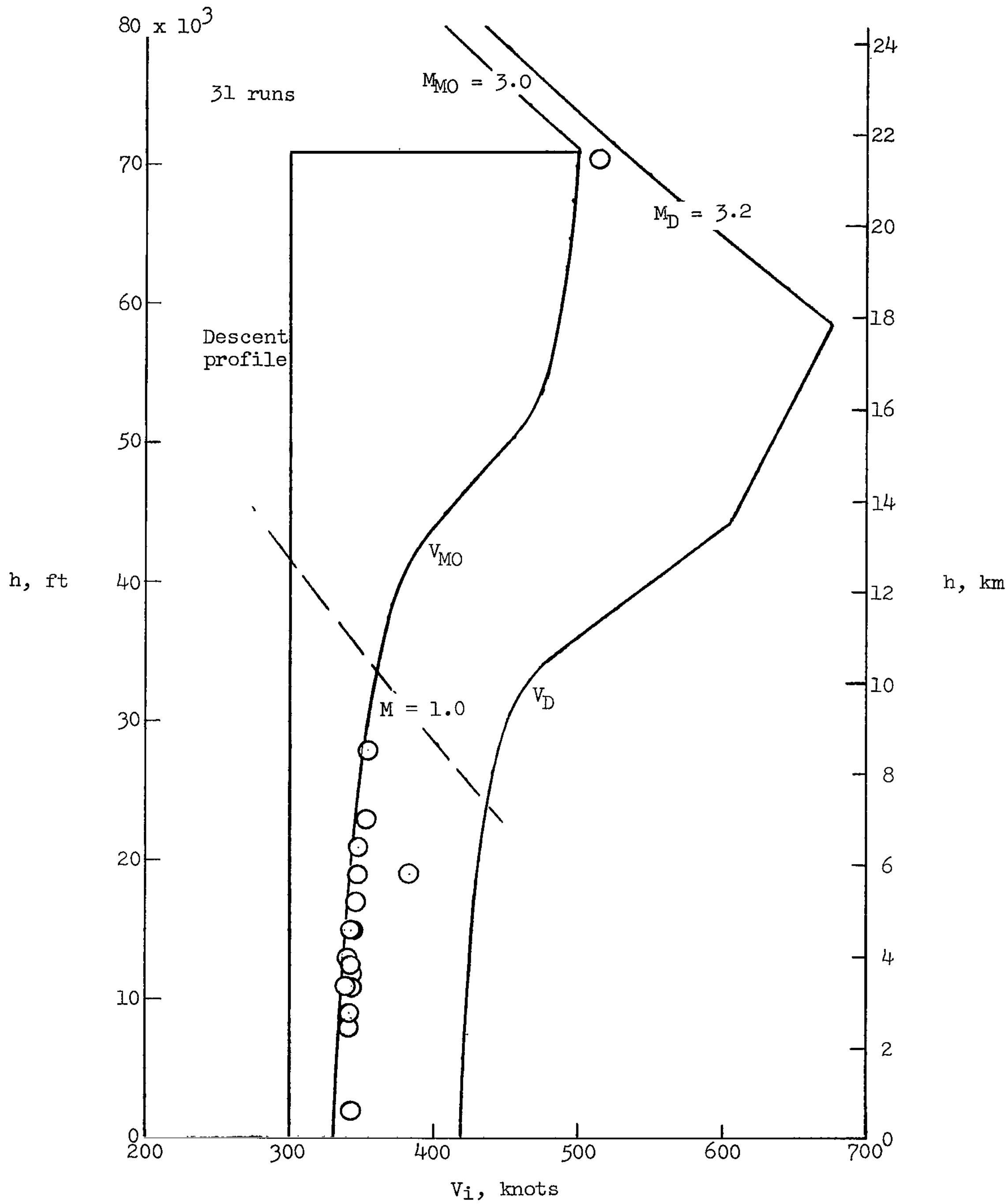


Figure 10.- Airspeed and altitude excursions resulting from step climbs.



(a) Departures.

Figure 11.- Maximum operating limit speed V_{MO} exceedences during simulated SST-ATC operation showing altitude where exceedence occurred and magnitude of exceedence.



(b) Arrivals.

Figure 11.- Concluded.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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